



April 26, 1972

Neutral Current, or Heavy Leptons?

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Contribution to  
"COMMENTS ON NUCLEAR AND PARTICLE PHYSICS"

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We might have seen the opening of a new avenue towards our unified understanding of weak and electromagnetic interactions of particles. Hopefully this event, if successful, may be compared with one of the most brilliant human achievement of the last century --the unification of electric and magnetic phenomena.

In the last year, very intense researches have been carried out in the hopes of unifying electromagnetic and weak interactions and constructing a finite (that is to say, renormalizable) theory of weak interactions. All these endeavors were inspired by Weinberg's paper in 1967<sup>1</sup> and Salam's in 1968,<sup>2</sup> in which they discussed a model of leptons which unifies electromagnetic and weak interactions in a Yang-Mills gauge theory and in which the observed dissimilarities between these two interactions, in particular, the mass of weak vector bosons, were attributed to a spontaneous breakdown of the gauge symmetry. (The so-called Higgs mechanism). The renewed interest in this direction in the past year was due to the brilliant observation of a young Dutch physicist, G. 't Hooft,<sup>3</sup> who gave a compelling argument that theories of the kind considered by Weinberg are renormalizable and physically satisfactory (in the sense that the unitarity of the S-matrix is preserved), as conjectured first by Weinberg. This correspondent feels confident, based on the work of his group,<sup>4</sup> that theories of this genre, when properly constructed, are finite in all orders of perturbation theory after renormalization.

It is not clear if we have as yet a model of electromagnetic and weak interactions for both leptons and hadrons, which is aesthetically satisfactory and which is in accord with all of our knowledge on semileptonic and nonleptonic weak interactions. It is equally unclear, today, if the nature makes use of any scheme based on the Yang-Mills gauge theory and the Higgs mechanism. Ultimately only experiments can tell us if it does.

In this note we shall discuss the high energy behavior of some typical weak interactions from the S-matrix viewpoint and deduce some conditions that a renormalizable model of unified weak and electromagnetic interactions must satisfy; we shall then discuss experimental implications of such conditions. We shall begin by accepting the validity of quantum electrodynamics and the following proposition: the observed weak interactions (such as the  $\mu$ - and  $\beta$ - decays) are mediated by charged vector bosons  $W^\pm$  coupled to charged weak currents.

Let us first consider  $\nu + \bar{\nu} \rightarrow W^+ + W^-$ . In the conventional theory this process goes via exchange of the electron in the t- channel (see Fig. 1). One finds that the amplitude for this process grows like  $s$  for large  $s$ :

$$f(\nu + \bar{\nu} \rightarrow W^+ + W^-) \sim e^{i\phi} \sin \theta \ s$$

where  $\Theta$  and  $\phi$  are the polar and azimuthal angles of the  $W^+$  in the center of mass system. The most violent growth at high energy occurs in the  $J = 1$  state with  $W^+$  and  $W^-$  polarized longitudinally. This linear growth with  $(\text{energy})^2$  of the amplitude for  $\nu + \bar{\nu} \rightarrow W^+ + W^-$  is responsible for the quadratic divergence of the amplitude for the elastic process  $\nu + \bar{\nu} \rightarrow \nu + \bar{\nu}$ , whose imaginary part is proportional to the absolute square of the former.

Therefore, in a renormalizable theory, where no divergence can be tolerated in a four-fermion coupling, the linear growth of Eq. (1) must be

suppressed. There are essentially three possibilities of suppressing this behavior in terms of renormalizable interactions. They correspond to adding single particle poles in the s-, t- and u-channels to cancel the leading term Eq. (1). Let us discuss them in turn.

A pole term in the t-channel (see Fig. 2) which entails the existence of a negatively charged lepton with the electron number +1 (the muon will not do here), cannot suppress the leading term of the electron exchange (Fig. 1), since the two terms have the same sign for large s, independently of the sign of the coupling constants involved.

The second possibility is to add a pole term in the s-channel. We need a boson of Spin 1 which couples to the neutrino-antineutrino pair (It cannot be the photon). See Fig. 3. In order that the cancellation of the leading term takes place for all helicities of  $W^+$  and  $W^-$ , the coupling of the neutral heavy vector boson Z to  $W^+$  and  $W^-$  must be precisely as in the Yang-Mills gauge theory. Weinberg's original model contains all these features.

The third possibility is to add a pole term in the u-channel and this calls for the existence of a lepton of the opposite electric charge and the same lepton number as the electron. (See Fig. 4). The model recently advanced by Glashow and Georgi<sup>5</sup> achieves the asymptotic vanishing of the amplitude  $\nu + \bar{\nu} \rightarrow W^+ + W^-$  by the cancellation of the  $e^-$  and  $E^+$  (heavy electron) exchange diagrams.

As we have seen, a renormalizable model of weak interactions must therefore contain one or both of the following two features:

(1) neutral current: we need a neutral vector boson  $Z$  which couples to it. The Weinberg model, which makes use of the group  $U(2)$  to unify electromagnetism and weak interactions, is of this type, where the photon,  $W^\pm$  and  $Z$  form a quartet of gauge vector bosons. When the hadrons are introduced into the scheme, we must somehow account for the absence (experimentally well verified) of strangeness-changing neutral current. This can be effected by introducing a fourth quark, as remarked by Glashow, Iliopoulos and Maiani in a slightly different context. (2) heavy leptons: The Glashow-Georgi (G-G) model is an example in which the asymptotic vanishings of the amplitudes for  $\nu + \bar{\nu} \rightarrow W^+ + W^-$  and  $e^+ + e^- \rightarrow W^+ + W^-$  are brought about by the exchanges of heavy leptons  $E^+$ ,  $E^0$  respectively. In order to incorporate the muon into this scheme, we need heavy leptons  $M^+$ ,  $M^0$  of the same muon number as  $\mu^-$ , as well as  $\nu_\mu$ .

Let us now consider experimental consequences of the two possibilities.

(1) neutral current<sup>7</sup>: The diagonal processes

$$\bar{\nu}_e + e \rightarrow \bar{\nu}_e + e,$$

$$\nu_\mu + e \rightarrow \nu_\mu + e,$$

receive contributions from the Z exchange in the t-channel. The latter is completely forbidden in the conventional Feynman-Gell-Mann theory. The present experimental evidences-- Reines-Gurr experiment for the former and the CERN neutrino experiment for the latter--do not rule out the Weinberg theory. As for the strangeness conserving hadronic neutral current, evidences for

$$\begin{aligned} \nu_{\mu} + p &\rightarrow \nu_{\mu} + p \\ &\rightarrow \nu_{\mu} + n + \pi^+ \end{aligned}$$

are somewhat ambiguous. Recent unearthing of an "ancient" evidence, based on the 1963-1965 Columbia-BNL experiment, shows that the process

$$\nu_{\mu} + p \rightarrow \nu_{\mu} + p + \pi^0$$

probably does not exist.<sup>8</sup> At NAL the "inclusive" neutrino reaction:

$$\nu_{\mu} + p \rightarrow \nu_{\mu} + \text{anything}$$

and the trident production in the nuclear Coulomb field:

$$\nu_{\mu} + (Z, A) \rightarrow \nu_{\mu} + e^+ + e^- + (Z, A)$$

should be looked for.

(2) heavy leptons: Let us consider  $M^+$ . It may be produced by the reaction

$$\nu_\mu + p \rightarrow M^+ + \text{anything}$$

According to Bjorken,<sup>9</sup> the production cross section for  $M^+$  relative to that for  $\mu^+$  is a function of  $s/M^2$  only, where  $M$  is the mass of  $M^+$ . He estimates that at  $s/M^2 = 20$ , the ratio is about 0.6.  $M^+$  is expected to decay as

$$\begin{aligned} M^+ &\rightarrow \nu_\mu + \nu_\mu + \mu^+ \\ &\quad \nu_\mu + \nu_e + e^+ \\ &\quad \nu_\mu + \text{hadrons} \end{aligned}$$

If the mass of  $M^+$  is about 1 GeV, its lifetime is about  $10^{-11}$  sec.

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Figure 1

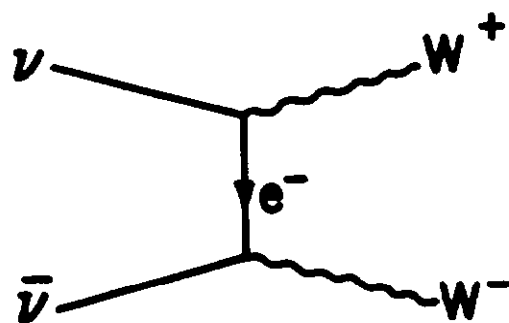


Figure 2

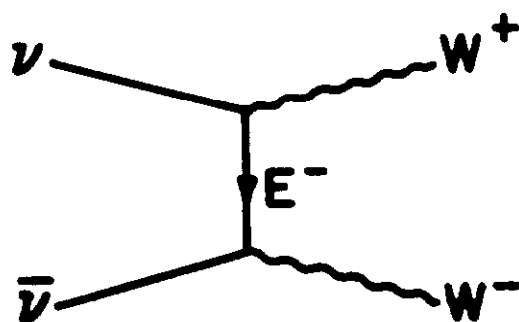


Figure 3

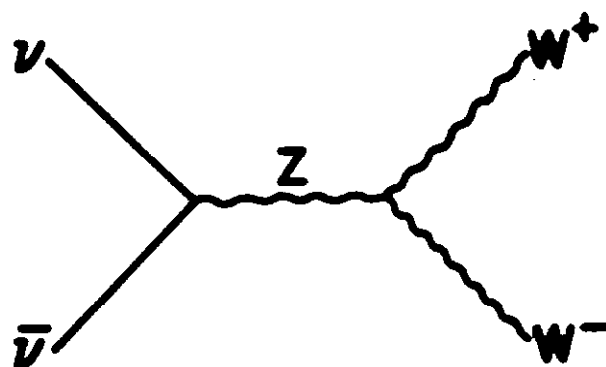


Figure 4

